

COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF AIRFLOW IN AN IDLE PASSENGER CAR CABIN

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ABSTRACT

Sunny conditions create the heating to the car body and rise in its average internal temperature resulting discomfort to the driver and passengers. It was observed that inside temperature of the car cabin rises up to 60⁰C - 70⁰C in summer during parking conditions. Consequently, it may be fatal to the life of a child, left inside the car due to some reason as reported in various news resources. In the present investigation, air circulation and temperature distribution in car cabin was studied to address the problem of heating and ventilation in the car cabin. The possible design criteria were instigated for geometrical consideration as an inlet vent was considered below the front windshield and outlet vent at below rear windshield. In another design concern, two outlet-vent were considered; one below and above the rear windshield. It was observed that air circulation in the rear compartment was more effective in comparison to the front compartment improving the overall air circulation with increase in inlet velocity. Also an increase in the uniformity of internal temperature distribution was observed with the increase of incoming airstream velocity. The temperature difference marginally improved for modified design conditions. The accumulated heat in the car cabin can be reduced appreciably with the provision of vents in the compartment.

KEYWORDS: Car-Cabin, Ventilation, Thermal Comfort, CFD & Vents

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1. INTRODUCTION

The primary objective of designing the heating and air-conditioning system of a passenger car is to achieve the optimum level of thermal comfort within specific time frame. In summer season, most of the areas of Indian subcontinent are extremely hot with average temperature ranging from 35⁰C–45⁰C. The effect of direct solar radiation on an automobile increases the overall temperature of passenger compartment. The effect of direct heating is more prominent when the passenger car parked in unshaded zone. In parking condition, all openings of passenger car are generally closed and falling heat on the body of the car is soaked by the internal air and material used in the various component used in the interior of the compartment. Hence, the rise of temperature in the range of 60⁰C–70⁰C was recorded inside the car compartment during the parking under direct sunshine [1].

The heating of the car body and rise in the average cabin temperature causes discomfort to the driver and passengers. Several solutions were prescribed and used by the car users to overcome or minimise the effect of heat like opening the doors of car to get cool down or run the air-conditioning unit to bring the temperature of the cabin to comfortable level etc. Apart from the comfort of the passenger, the life of the interior and the goods gets degraded with the high internal temperature.

It has been observed through various studies of literature, news resources and hospital studies that heat accumulation inside the car compartment and ventilation problem causes a number of deaths of children, left unattended inside the compartment due to various reasons [2, 3]. Forty two children fatalities occurred in USA in the year 2017 due to vehicular heatstroke and the yearly average of such deaths from 1998 to 2017. Hence, in nineteen years duration, there were (37 children fatality with the total of 742 [4].

Saidur et al. [5] studied a modified commercial ventilation system to investigate steady state temperature and increase in air flow rate inside the car compartment. They observed that the solar radiation was the prime factor of cooling load on vehicle air-conditioning system.

Huang et al. [6] observed that the greenhouse-control system operated by solar battery, can be used to remove hot air from the car during idling of the engine. Torregrosa-Jaime et al. [7] developed a thermal model of cabin of automotive minibus and studied the dynamics of cool-down and warm-up in outdoor conditions. They concluded that major cooling load requirement is due to the solar radiation and solar radiation plays an important role in thermal environment in the cabin. Giri et al. [8] found that problem due to heat accumulation in the compartment of a car and improper ventilation has a serious concern during parking. They have suggested that active or passive ventilation shall be investigated for saving the lives and reducing the fuel consumption in an automotive compartment. Finn et al. [9] designed and experimentally validated a car safety seat with thermoelectric cooling to effectively survive a child in closed vehicle parked in sunshine for up to 95 minutes.

Jalil and Alwan [10] carried a two-dimensional numerical study of vehicle cabin of a passenger car for air flow and temperature using the two-equation $k - \epsilon$ turbulent model and found that the inlet temperature and inlet velocity along with number of inlets in the cabin has the effective role to modify the efficiency of an air-conditioning system. Lee et al. [11] conducted extensive CFD simulation to study the effect of solar radiation on the flow field and temperature distribution in passenger car and observed that there was strong movement of air flows near the front seat. Sanaye et al. [12] estimated the thermal and ventilation load in the cabin of a vehicle and modeled the outgoing and circulated air with the fuzzy controller. They found shorter time to control the temperature of the cabin during operation of the heating, ventilation and air conditioning system.

Presently, very limited researchers are working to study the heat accumulation in the cabin. Most of the researchers have investigated the air flow and temperature distribution within the compartment for initial warm up or cool down period. The present work was carried out to analyse the role of ventilation and reduction in the temperature of the cabin under parking condition. Although, the configuration and geometry of interior of car was complex in three dimensional distributions, but a two-dimensional flow simulation would give many important characteristics of buoyant air flow within the compartment. Flow inside the car compartment is likely to be laminar or weakly turbulent due to low air velocity.

2. PROBLEM FORMULATION

Present investigation considered two-dimensional, steady, laminar, incompressible flow with Boussinesq's approximation. The Physical properties were assumed to be constant for all calculation and solution domain. The standard Navier-Stokes equations and energy equation were solved numerically with CFD software (Ansys Fluent V.14.0) with SIMPLEC algorithm due to Doormaal Van et al. [13] for the velocity and temperature distributions. A longitudinal central

plane of car compartment has been considered for the analysis of the airflow and temperature distribution. The flow of air was considered for a fixed inlet and different outlets positions with varying velocities at inlet vent in the compartment of the car.

2.1. Governing Equations

The following governing equations have been used for various flow parameters within the car compartment. The standard form of the continuity equations is shown in eq. (1). The conservation of x-momentum and y-momentum have considered as shown in eq. (2) and (3) respectively with the energy equation eq. (3).

Continuity equation (Conservation of mass):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Conservation of x-momentum:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

Conservation of y-momentum:

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - g \quad (3)$$

Energy conservation equation:

$$\rho C_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \phi \quad (4)$$

Where, ϕ = dissipation function of energy

$$= \mu \left\{ 2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 \right] + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 \right\}$$

2.2. Geometry and Boundary Conditions

Actual size of a small Maruti ALTO™ car have been considered for analysis as shown in **Figure 1** with two different configurations of vent positions:- Case-A has one inlet and one outlet vent while in case-B, one inlet and two outlet vents have been considered. Here, 'w' represents the size of inlet vent and 't' represents the size of outlet vent. The size of vent was considered as 0.15m for inlet and 0.15 m for outlet.

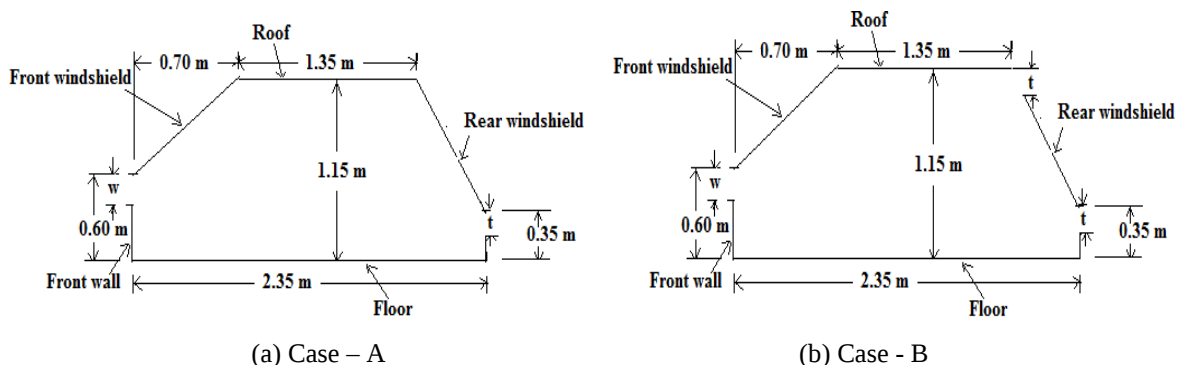


Figure 1: Car Geometry with Inlet and Out Vents

The boundary conditions were considered as per the experimental data by Chien et al. [14]:

Roof: heat flux 202 W /m²,

Front wall: heat flux 112 W /m²

Floor: heat flux 35 W /m²

Mixed (convection and radiation) boundary condition at front and rear windshield: Free stream temperature is taken as 40 °C, external emissivity as 0.88. Convective heat transfer co-efficient [15];

$$h = 1.163 (4 + 12\sqrt{v}) \text{ W / (m}^2 \cdot ^\circ\text{C)}$$

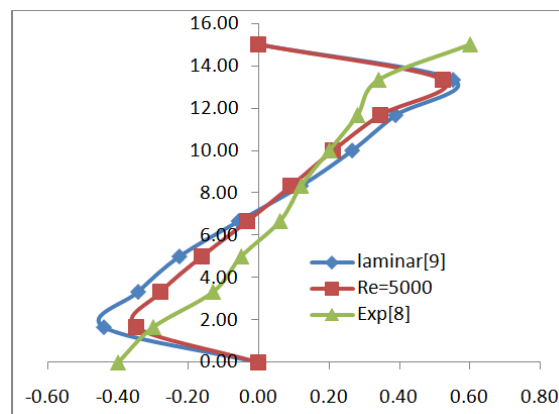
Where, v = wind speed relative to car, m/s

Inlet: velocity inlet, temperature 40 °C

Outlet: pressure outlet, gauge pressure = 0

2.3. Numerical Solution Procedure

The computational domain was meshed into triangular cells of 13703 nodes and 26880 elements and grid-independence test has been performed in order to ensure accuracy of the mesh results. Scheme for pressure-velocity coupling were SIMPLEC and for discretization of momentum and energy equation was adopted as first order upwind. The convergence criteria for x-velocity, y-velocity, continuity and energy have been approximated to 10^{-3} , 10^{-3} , 10^{-4} and 10^{-6} respectively.



X-axis: u/U (non-dim velocity), Y-axis: y/w

Figure 2: Comparison of Velocity Profile at $x = 2/3 L$.

The numerical results have been validated with the reported experimental results by Neilsen [16] and numerical solution of Tripathi and Moulic [17]. The inlet and outlet were located at top of front windshield and bottom wall of rear goods cabin respectively. For validation of the result inlet velocity was 0.455 m/s and $Re = 5000$. It has been observed that the profile of x-velocity (u) at vertical cross-section (**Figure 2**) in rear passenger compartment ($x=2/3 L$) were in good agreement with the standard solutions [16, 17].

3. RESULTS AND DISCUSSIONS

The computed results of streamlines and isotherms were shown in the **Figures 3 and 4** respectively for case-A with inlet at bottom of the front-windshield and outlet in the goods cabin below the rear-windshield. All investigation assumed the summer condition with ambient temperature of 40°C and different wind speeds of 0.1 m/s, 0.2 m/s, 0.25 m/s and 0.3 m/s. It has been found that with increase in the air inlet velocity, the circulation of air in rear compartment of car improved drastically.

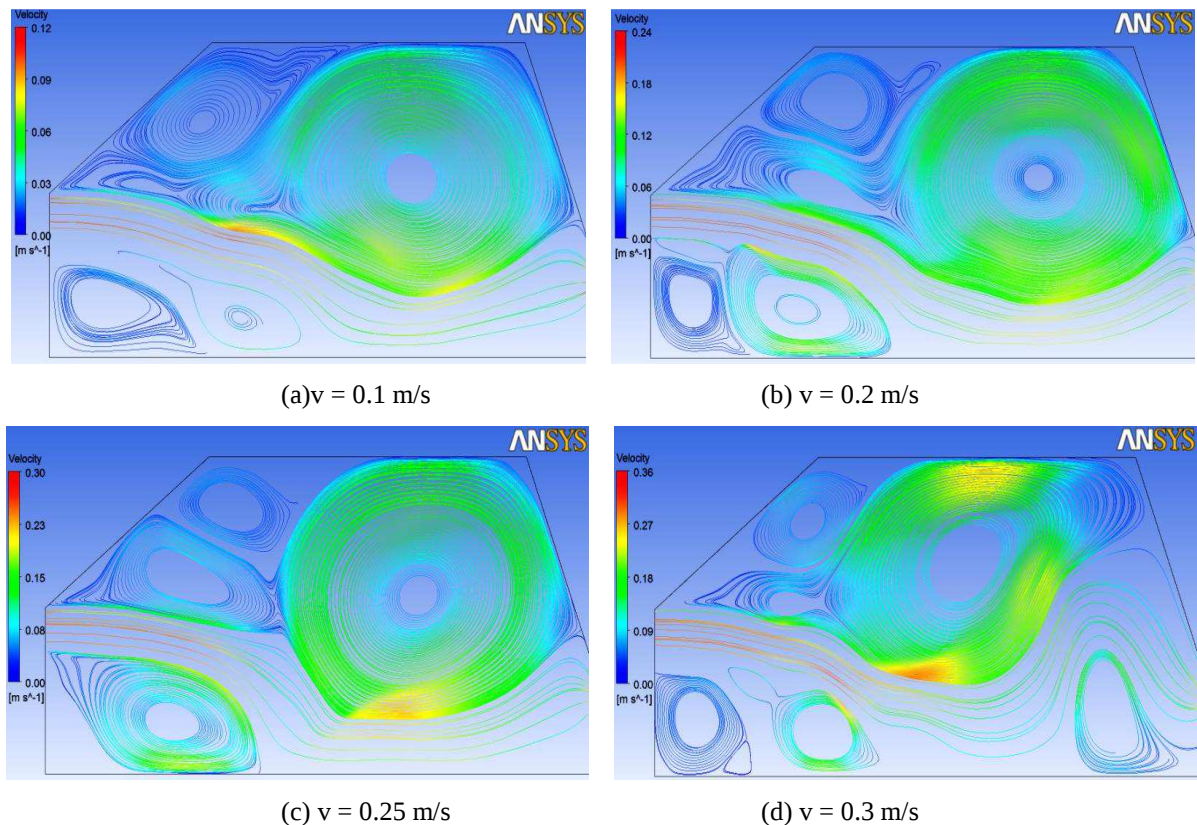
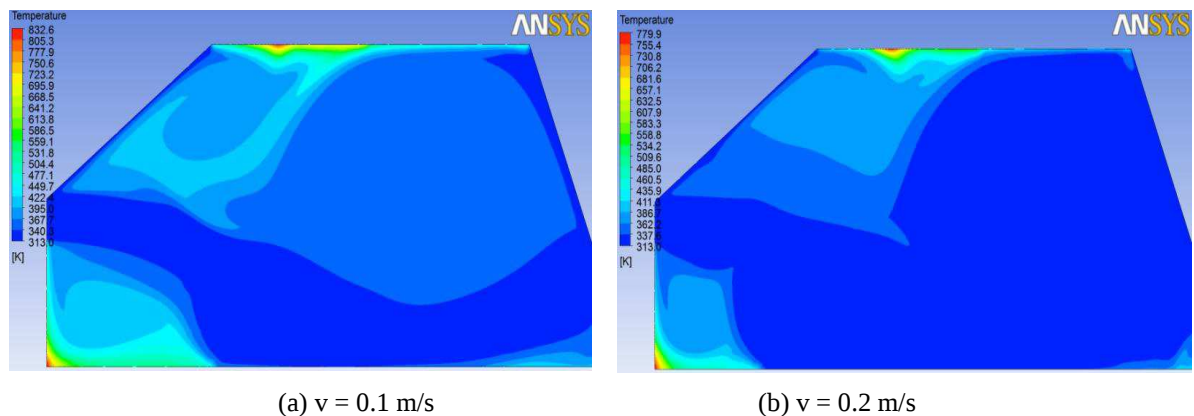


Figure 3: Streamlines for Case - A

It was observed that with the increase in the inlet velocity, an increase in the uniformity of the temperature in the car was observed. The temperature distribution near the roof and floor was not so satisfactory. There was less uniformity of temperature in the front compartment with low inlet velocity and uniformity gets propagated towards the front compartment from rear compartment with the increase in the inlet velocity.



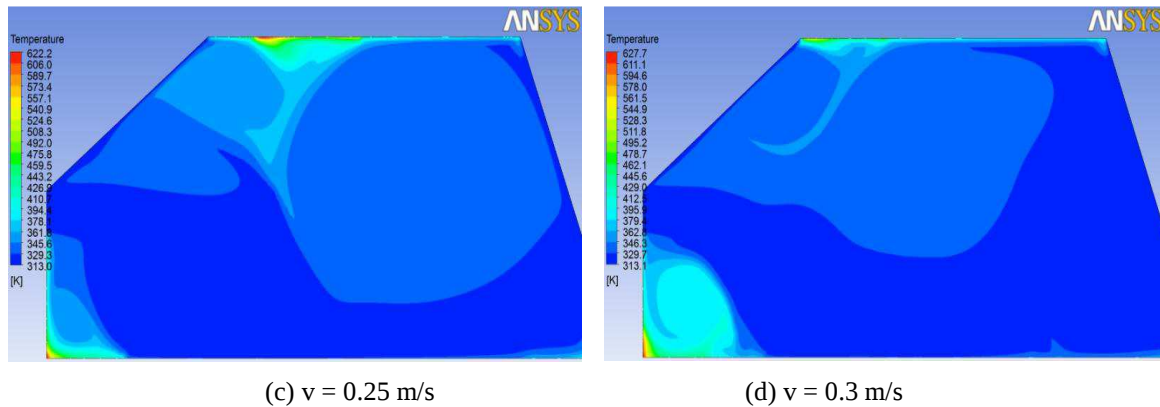


Figure 4: Isotherms for Case -A

The pattern of air movement in rear compartment was almost same in all cases, whereas air movement in front compartment of car improved with the increase in the inlet velocity.

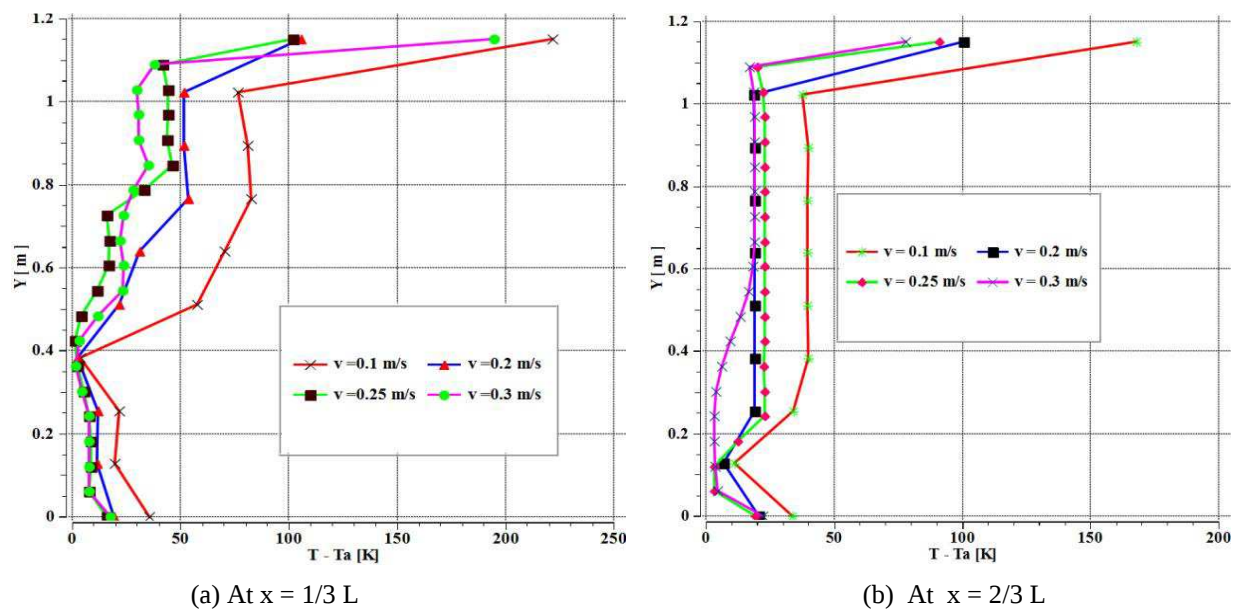


Figure 5: Comparison of Temperature Profiles for Case-A

The temperature profiles (Figure 5) at vertical cross-sections in rear passenger compartment ($x=2/3 \text{ L}$) and front compartment ($x=1/3 \text{ L}$) for different inlet velocities depicted that with increase in the inlet velocity, the cabin temperature reduced and difference between ambient temperature and cabin temperature decreases. Only at top of the cabin i.e. at nearby roof, temperature was not observed to be satisfactory. The difference of temperature reduces from 300°C to 100°C with the increase in the inlet velocity from 0.1 m/s to 0.3 m/s in the cabin except at nearby walls.

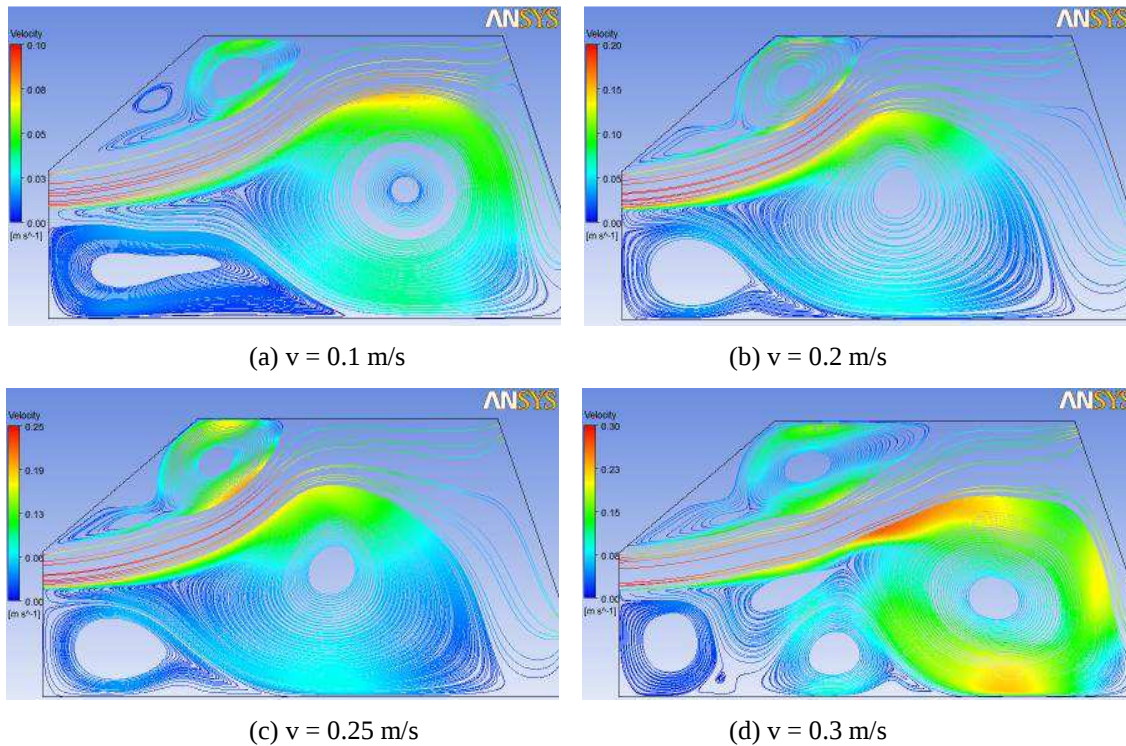


Figure 6: Streamlines for Case-B

Figures 6 and 7 investigated the isotherms and streamlines for case-B with inlet at the bottom of the front-windshield and two outlets (one in goods cabin below the rear-windshield and other one at the top of rear- windshield). The pattern of air movement in the rear compartment was almost same for all velocities but air movement in the front compartment of the car improved with the increase in the inlet velocity.

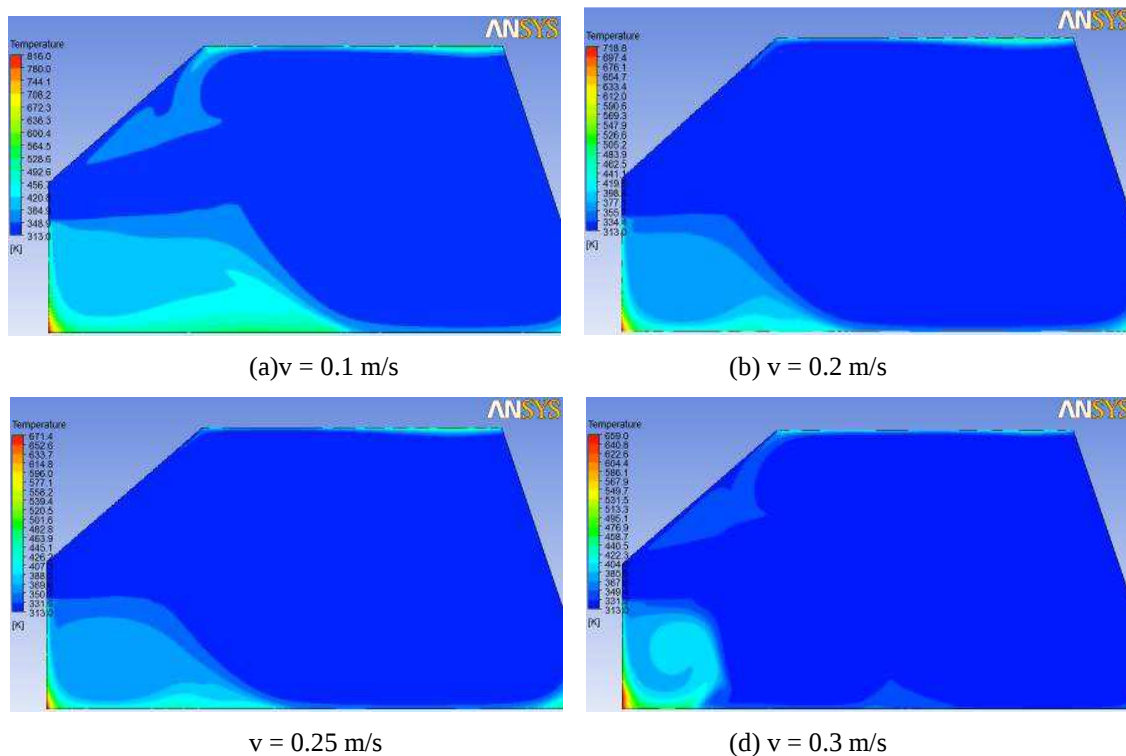


Figure 7: Isotherms for Case-B

It was found that with the increase in inlet velocity, the uniformity of temperature in the car increases. It was showed that uniformity in the temperature increases with respect to case-A and overall temperature of the compartment was reduced in comparison to case-A.

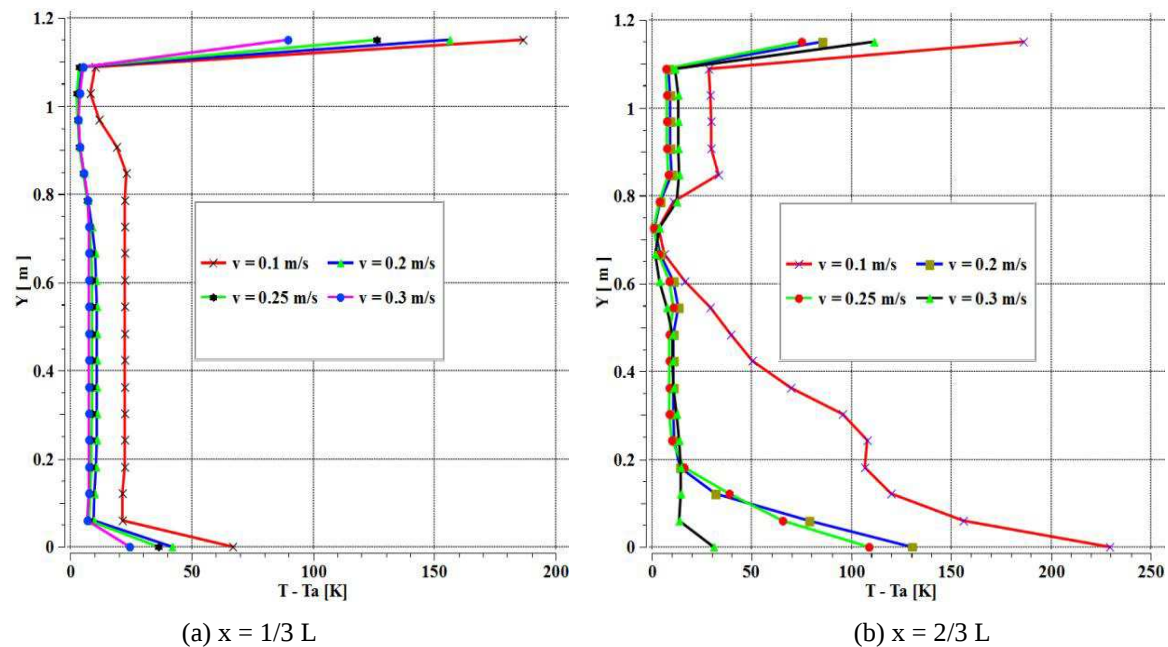


Figure 8: Comparison Temperature Profiles for Case-B

The temperature profiles (**Figure 8**) at vertical cross-sections in rear passenger compartment ($x=2/3 L$) and front compartment ($x=1/3 L$) for different inlet velocities showed that overall cabin temperature reduced and difference between cabin temperature and ambient temperature decreases with the increase in the inlet velocity. The temperature profiles were not observed to be satisfactory only at top of the cabin i.e. at the roof, and difference of temperature reduced from 20°C to 8°C with increase in inlet velocity from 0.1 m/s to 0.3 m/s in cabin except nearby walls.

4. CONCLUSIONS

The investigation showed that the circulation of air in the rear compartment of the car was efficient enough and improved with the increase in the inlet velocity. In case-A, the temperature in the front compartment was higher and similarly less uniform. The overall temperature difference in cabin with respect to ambient temperature was from 30°C (at 0.1 m/s inlet velocity) to 10°C (at 0.3 m/s inlet velocity). In case-B, the improvements in overall temperature and air circulation of the car compartment have been observed. The temperature difference of compartment with respect to ambient temperature was improved to 20°C to 8°C .

The vents in the compartment can reduce the temperature of the cabin in parking condition and consequently reduce the energy consumption for operation of air-conditioning system. The risk of heatstroke and suffocation in the hot weather conditions particularly in summer may also reduced. Minor changes in the inlet / outlet design can improve the air circulations in the car compartment and overall reduction in the average temperature of the cabin.

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